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14. ABSTRACT  The electrical resistivity of the ground can be measured by several methods. One, which has proven useful, is the controlled source magnetotelluric method (CSAMT). Current over a wide range of frequencies is introduced into the earth through a grounded dipole. Then the resulting electric and magnetic fields are measured at a distance greater than several skin depths. The apparent resistivity is then calculated by: $\rho = 1/5f [E/B]^2$ . The apparent resistivity vs. frequency can be converted into true resistivity vs. depth. This grant involved an investigation into the HAARP virtual antenna pattern out to 200 km, and its use as a CSAMT transmitter.						
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Final Report  
ONR Grant No. N00014-97-0995  
"Geophysical Electromagnetic Sounding Using HAARP"

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**Co-Principal Investigator:** Davis D. Sentman

## INTRODUCTION

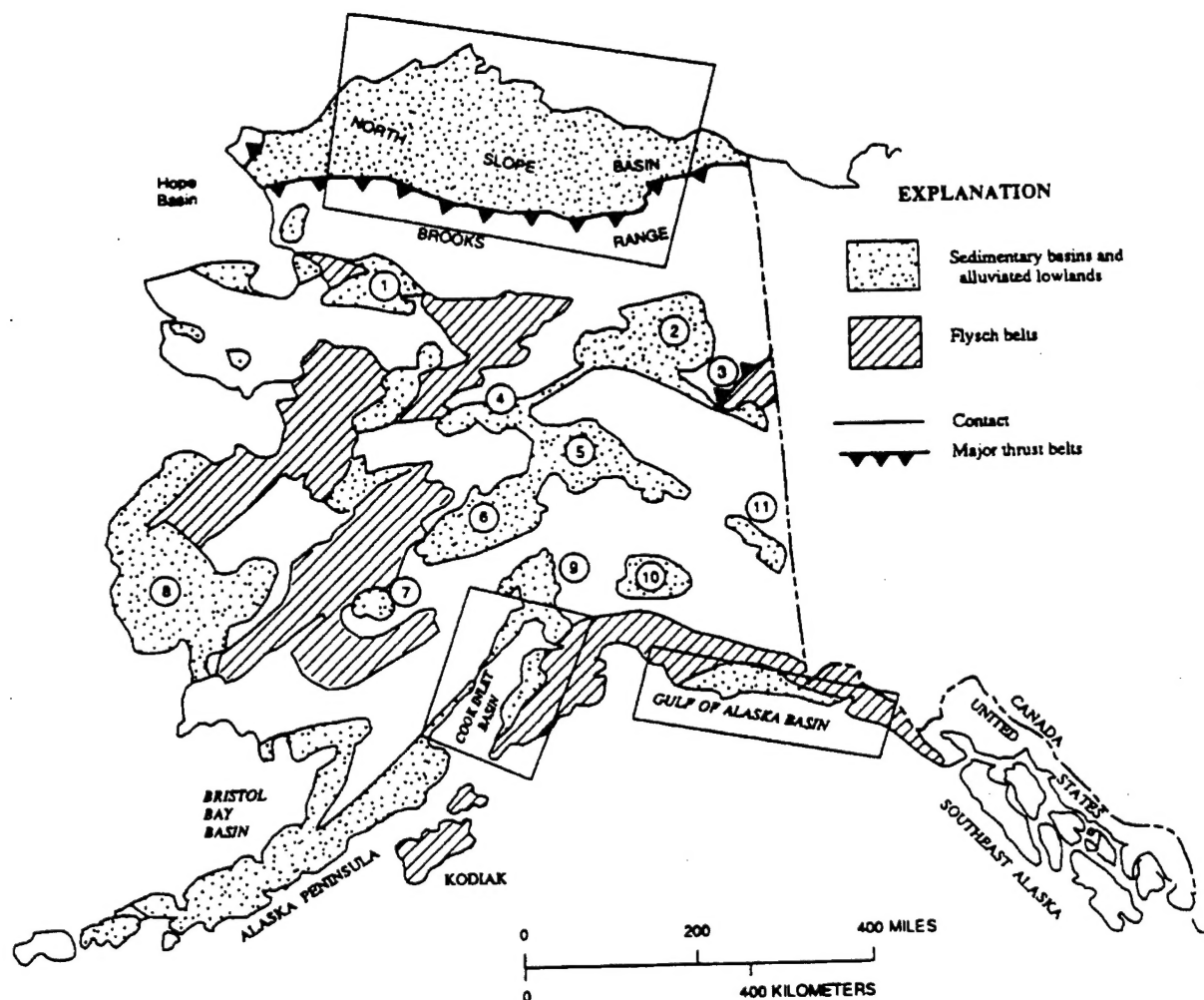
Methods of geophysical exploration belong to one of four main categories: seismic, potential field (gravity and magnetics), electrical, and radiometrics. Each method has specific capabilities and advantages, as well as limitations, for use in exploration for various commodities. Electrical methods have been found to be particularly effective in the search for metallic ores and ground water, where they are the geophysical method of choice. Electrical methods are also widely used in conjunction with other methods in important applications, such as in the exploration for oil and gas, in geothermal energy evaluation, in environmental monitoring and engineering studies, and in the exploration of the Earth's crust as fundamental research.

The use of geophysical measurements that detect the electrical conductivity of the earth has been standard technology for the past half century in engineering applications and in the search for mineral, petroleum, and geothermal resources. Often, the methods are cumbersome when applied on a detailed scale in the search for local deposits of economic minerals, geothermal reservoirs or hydrocarbons. Exploration for such resources is hindered in frontier areas, such as Alaska, because of the high cost of exploration in an area where adequate reconnaissance exploration has not been carried out to define prospective areas with confidence.

This, of course, is not the full story. Seismic reflection surveys are surely the method of choice in exploration in a mature environment; they provide very high resolution in mapping the subsurface, particularly in areas where the subsurface character is already well known. However, high-quality seismic surveys are expensive in even the most accessible of areas, and prohibitively expensive in remote areas, particularly those where there is no prior information on the character of potentially hydrocarbon-bearing rocks. Therefore, many frontier areas remain unexplored today because of costs.

In the contiguous 48 United States, electrical methods have not been very useful in exploration for oil and gas, primarily because of the maturity of the industry. So much is known about the subsurface, and the region is so easily accessible, that deployment of high-resolution seismic surveys is warranted as an initial exploration effort. In more remote areas, including Papua-New Guinea, the Myanmar Republic, Venezuela, onshore Africa, and the Astrakhan Arch and East Siberia provinces of the Soviet Union, electrical methods are being used with a high degree of success as the lead method for exploration.

Alaska can still be considered a frontier area for oil and gas exploration. Figure 1 is a map of Alaska showing the three known onshore oil and gas provinces and eleven other sedimentary basins that have not been explored extensively. Deployment of seismic reflection surveys either



**Figure 1.** Oil and gas provinces and sedimentary basins of Alaska

onshore or offshore Alaska is an expensive undertaking, and onshore surveys involve major problems with environmental damage, considering the fragility of much of Alaska's ecosystem. The use of electrical methods to evaluate the potential for hydrocarbon occurrence in Alaska is a natural and reasonable step forward. A specific example appropriate to Alaska can be cited. Suppose the Brooks Range is an overthrust structure covering the southward extension of the sedimentary section containing oil on the North Slope. The overthrust would hide from surface exploration any rocks beneath. Seismic exploration would be expensive, invasive, and because of the lack of prior information, would have to be done in a shotgun-like approach. Electrical exploration, on the other hand, can be done less expensively, non-invasively, and clearly outlining any hidden volume of potentially petroleum bearing rocks beneath the overthrust.

The effectiveness of electrical methods for identifying prospective areas for the occurrence of oil and gas is based on the fact that oil and gas occur primarily in porous, salt water saturated rocks. Such rocks are uncommonly conductive, in the electrical sense. About 50% of the world's oil is

produced from sections of sedimentary rocks that have electrical resistivity,  $\rho$  of 2 to 5  $\Omega$ -m; about 90% is produced from rocks with resistivity in the range from 1 to 20  $\Omega$ -m, and 99.9% is produced from rocks with resistivity in the range from 1 to 100  $\Omega$ -meters. In comparison, the median resistivity for all rocks in Earth's upper crust is about 100  $\Omega$ -m. Therefore, a survey, which classifies the rock to drillable depths, say 10 kilometers, on the basis of electrical  $\Omega$ -m resistivity, will outline the areas within which oil can be expected to occur with a high degree of reliability.

An important group of electrical geophysical exploration methods involves the observation and evaluation of electromagnetic fields. The sources of the electromagnetic fields are: either natural, being the random concentrations of currents in the ionosphere and magnetosphere that take place all the time in a somewhat, mostly unpredictable, manner or; controlled, being fields generated at the surface of the earth by passing current into a pair of grounded electrodes, or along a cable. As such fields travel into the earth, they induce current flows that characterize the subsurface structure. Observation of the secondary electromagnetic fields accompanying these induced currents permits us to "image" the subsurface. These methods are used for many applications, ranging from academic studies of the earth's crust, to exploration for all sorts of commodities, such as economic minerals, geothermal reservoirs, ground water, and oil and gas. Many thousands of such measurements are made each year around the world.

The magnetotelluric method (MT) can produce a resistivity vs. depth profile by measuring naturally occurring, crossed electric (**E**) and magnetic (**B**) components and their phase angles over a wide range of frequencies. The audio magnetotelluric (AMT) method uses natural signals in the ELF and VLF bands. The apparent Cagniard resistivity is:

$$\rho = 1/5f [E/B]^2, \text{ where } E \text{ is V/m, } B \text{ is nT, } f \text{ is Hz and } \rho \text{ is in } \Omega\text{-m.}$$

The depth of investigation is approximately the skin depth:

$$D = 500[\rho / f]^{1/2} \text{ in m.}$$

The use of ultra low frequencies can be used to explore the earth to depths of order 10 km while the near surface is sampled by vlf frequencies. Although very sophisticated methods have been developed for analyzing the data it is often sufficient to derive a resistivity vs. depth profile using an approximate transformation based on simple asymptotic expressions introduced by *Bostick* [1977].

An improved variation of this technique is the Controlled Source Audio Magneto-Telluric (CSAMT) method. By the use of a large generator (30 kW), transmitter controller and transmitter, constant current using a square or sine wave at various frequencies is injected into the earth via a pair of grounded electrodes. The resulting **E** and **B** components vs. frequency are measured at a distance much greater than the skin depth. The method is limited by the amount of current that can be introduced into the ground, and a fairly large crew is needed. Transmitted voltage and current can be lethal, and the electrodes must be guarded to prevent injury or death to people or animals. The distance from the current dipole for practical exploration is only a few tens of km.

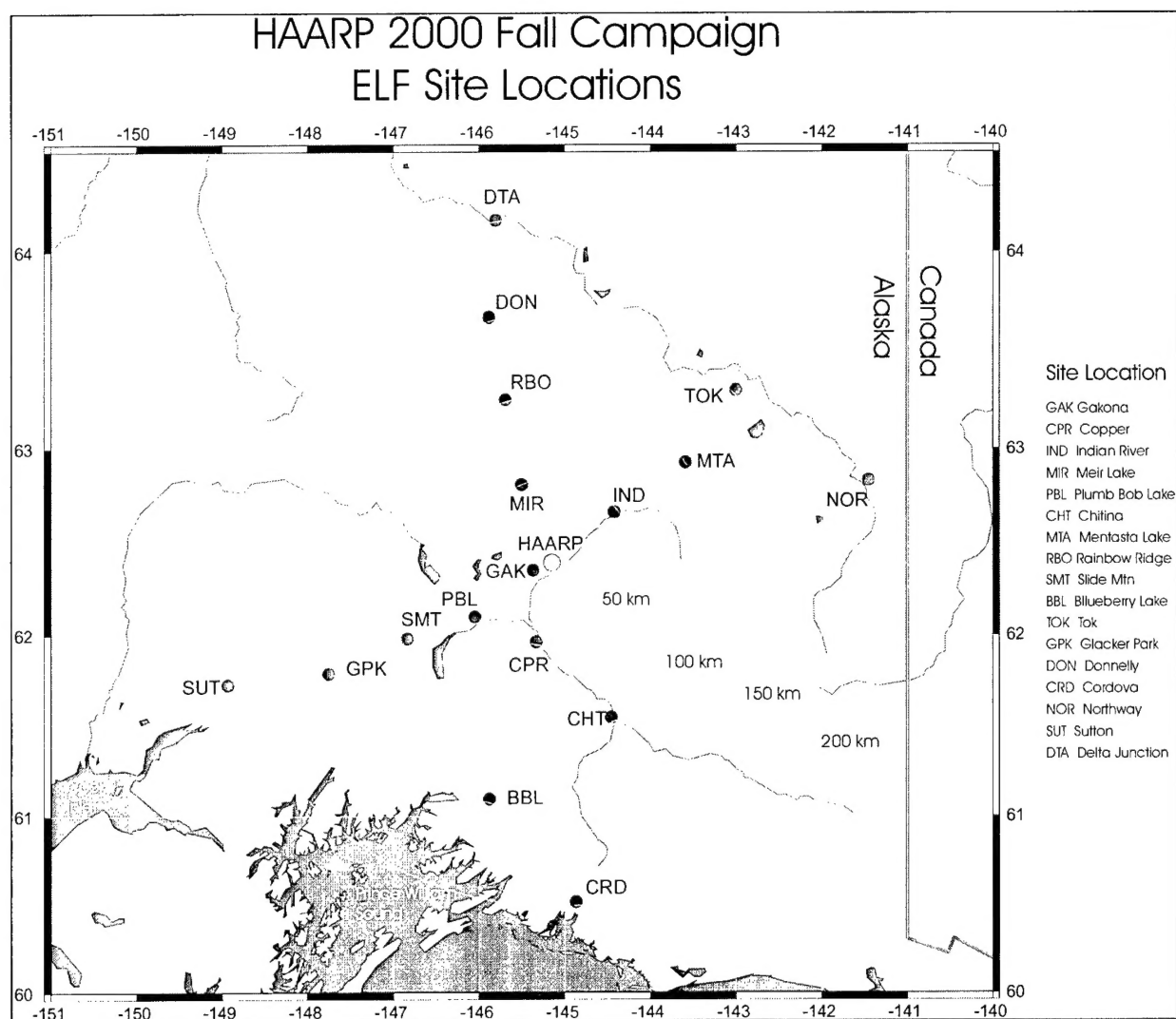
The HAARP and HIPAS transmitters can produce a virtual antenna at the bottom of the ionosphere by modulating the transmitted beam at frequencies from ulf to vlf. Although the effective signal is of the order of a few pT, with sophisticated data analysis the signal has been shown to be useful as a CSAMT transmitter within hundreds of km distance from HAARP, or over much of Alaska. The aim of this research was to develop instruments and software to use HAARP and HIPAS as CSAMT transmitters and to test the technique for practical applications to explore Alaska's geology and resources. The scope of the work was enlarged to determine the virtual antenna pattern of HAARP. Equipment was purchased or leased from Zonge Engineering, which after major modifications, was used for the measurements. The work was successfully accomplished, and examples of the results are presented in this report. The research showed that HAARP could be used successfully as a CSAMT transmitter, at least in the range of 4 to 8000 Hz, and to a distance of 200 km. It remains to be demonstrated that the frequency range below 4 Hz, which is necessary for gas and petroleum exploration, can be used with HAARP as a transmitter.

### **Preliminary Measurements**

The first experiments carried out were made using natural source AMT and HIPAS signals at a site on Himalaya Road off the Elliot Highway 53 km distance from HIPAS, in June 1998. This site is about 5 miles beyond the end of 60Hz power. Excellent natural source AMT measurements were obtained, but the HIPAS signals presented a problem. The E-field signal was large, the third harmonic was even larger than the base, but there was little or no magnetic signal. We were using 50m spacing between the grounded electrodes, which turned out to be almost exactly half the broadcast wavelength. The electrode to ground resistance was large and thus we had constructed a nice half-wave antenna. Using a voltage follower amplifier at each electrode and shielded cables with an electrode-to-electrode spacing of 70 m solved the problem.

### **Sites for Antenna Pattern Measurements**

As all of Alaska is owned by someone, the State of Alaska, Federal Government agencies including the National Park Service, the Forest Service and the Bureau of Land Management, various Native Corporations and Village Corporations, and private individuals. Therefore we had to obtain permission to do field work at the sites we picked off the map as being likely to be quiet and accessible from the highway system. In June 1998 a preliminary survey was conducted of sites at 50, 100 and 200 km distance from HAARP to determine the suitability of 12 sites, as the minimum we would need in the survey. At each site we used the natural electromagnetic noise from the ionosphere in the audio magneto telluric (AMT) method to determine the background noise spectrum and the ground resistivity vs. frequency. We also measured 60 Hz power line and harmonics noise for interference. Likely sites at 150 km distance were also located, but due to shortage of time were not measured for magnetotelluric resistivity. Figure 2 shows the 16 sites surveyed in relationship to HAARP and the Gakona magnetometer site.



**Figure 2.** Map of Alaska showing the location of HAARP, the Gakona magnetometer site, and the 16 remote sites used for the antenna survey and CSAMT measurements in Fall, 2000.

### Preliminary Experiments

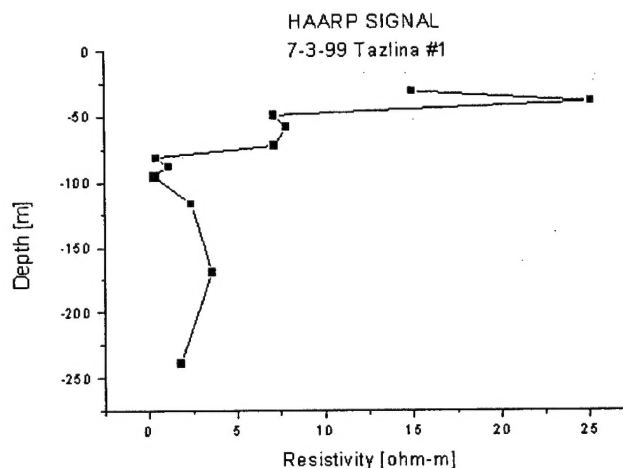
Following the 1998 RF Ionospheric Interactions Workshop, Gene Wescott visited Zonge Engineering in Tucson AZ to discuss changes in hardware to the GDP 32 II data recorder system and software needed to record HAARP transmissions for the proposed antenna pattern survey, and to be able to use the equipment for controlled source magneto telluric (CSAMT) resistivity vs. depth exploration with HAARP as the controlled source. After making some engineering modifications to the data recorder system, the equipment and software was delivered in time for fieldwork during the HAARP June/July 1999 campaign.

First tests were made in conjunction with HAARP transmissions. Observations were made from the site near a capped wildcat well, Tazlina # 1 located about 75.6 km from HAARP on the Lake Louise Road in July, 1999. The site is about 6 miles away from any 60Hz power lines, and proved to be a very quiet location. The advantage of this site for testing the method is that the



well was electrically logged, so the true resistivity is known. After several nights of unsuccessful tests, on the night of July 3, HAARP was modulating the beam at frequencies at powers of 2 from 4 Hz to 8192 Hz and very strong signals were received.

The HAARP signal apparent resistivity vs. frequency was converted to resistivity vs. depth using the Bostick algorithm as shown in Figure 3. Some minor smoothing was required for a few points. The results from the  $E_y/B_x$  apparent resistivity are shown in Figure 3. The resistivity log from Tazlina #1 starts at a depth of 340 m, because the well was cased to that depth, so we cannot compare the log and the CSAMT data directly. The logged resistivity starting at 340 m depth is almost constant at 5  $\Omega$ -m, in reasonable agreement with our deepest values from about 75 to 240 m as shown in Figure 3. The obvious sediments near the surface at the site are well-rounded river sediments and silts compatible with the 20-to 25  $\Omega$ -m values measured with the CSAMT closest to the surface.



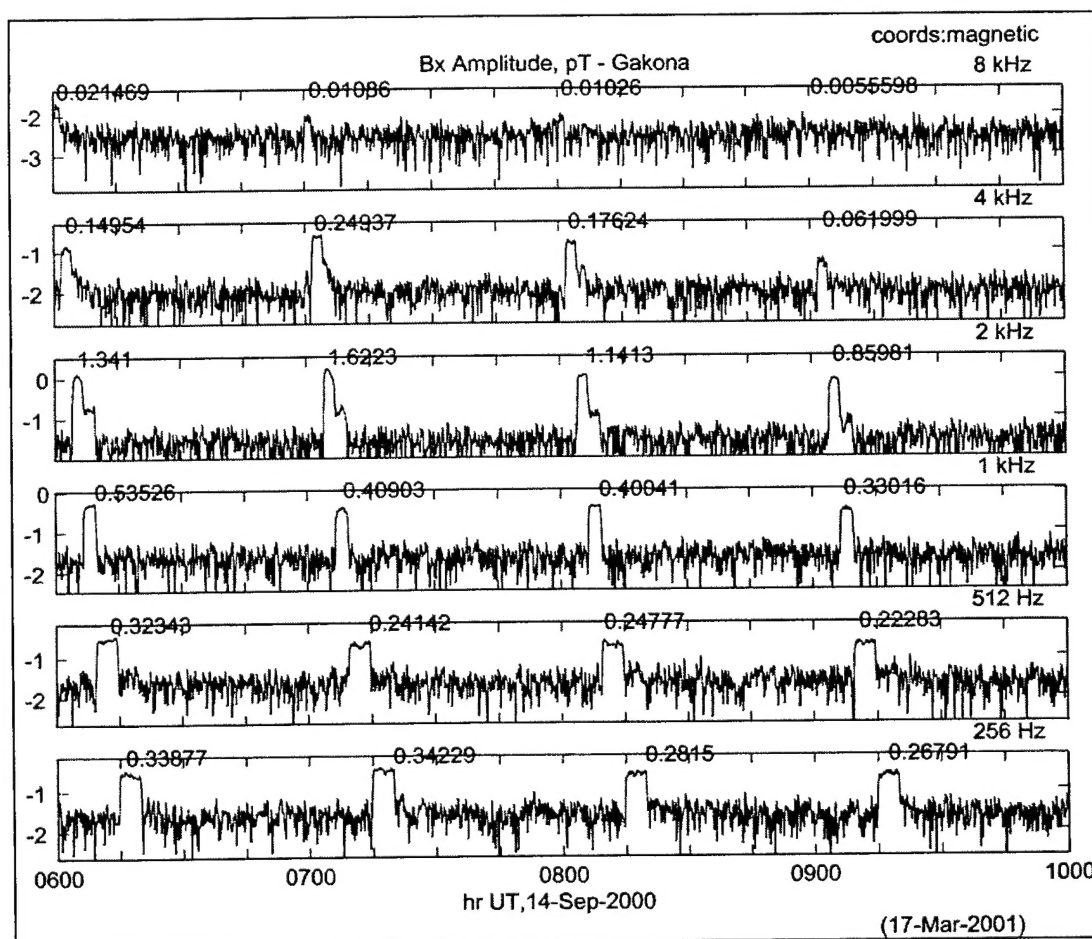
**Figure 3.** Bostick resistivity approximation vs. depth for Tazlina #1 well on the Lake Louise Road, 76 km from HAARP.

During the September/October 1999 HAARP campaigns, more preliminary measurements were made at several sites to test our equipment and analysis techniques that were subsequently used for the antenna pattern survey and characterization and CSAMT resistivity measurements. We successfully measured two components of  $\mathbf{B}$  and the corresponding  $\mathbf{E}$  fields at sites 50 km and 100 km from HAARP at frequencies: 16, 32, 64, 128, 256, and 512 Hz. The analysis of the data used a modified version of software used in the synchronous detection modules of the Gakona and Poker Flat systems. Following this successful test, plans were made to lease three specially modified data loggers for the full antenna pattern measurement campaign in the 2000 fall campaign. This would permit making measurements from four sites simultaneously. With this scheme it was decided to use the four systems distributed approximately in four quarters on circles centered on HAARP at distances of 50, 100, 150 and 200 km. as shown in Figure 2.

### Fall 2000 Campaign

Permission for an extended field campaign in September 2000 was obtained from all the pertinent landowners, and a contract was let for the lease of three Zonge GDP 32-II data loggers and magnetometer coils. Four crews operating from rented motor homes to provide accommodations at the remote field sites carried out all the antenna pattern field and resistivity measurements. The motor homes were equipped with generators for providing 60 Hz power for recharging batteries and transferring the data to digital tape. In order to reach the 200 km distance site about 40 miles from Cordova, a charter aircraft was flown from Valdez.

The field campaign began on September 5, 2000 with measurements of both **E** and **B** components at 4 sites each 50 km distant from HAARP. Observations at each distance group of sites continued on successive nights until the HAARP magnetometer coils at Gulkana indicated strong signals. Then all crews moved to the next distance sites. Excellent data were obtained on the UT nights of 7 September at 50 km, 8 September at 100 km, 12 at 150 km and 14 September at 200 km distances. (UT). The very best night of ELF/VLF activity occurred on the night of September 14. Figure 4 shows the **B<sub>x</sub>** amplitude vs. time from Gakona for frequencies 256 Hz to 8 kHz. Note that the second harmonic has been generated by the interaction with the ionosphere even though a pure sine wave was transmitted.



**Figure 4.** Synchronously detected signals 256-4000 Hz in **B<sub>x</sub>** in during the Fall 2000 campaign.

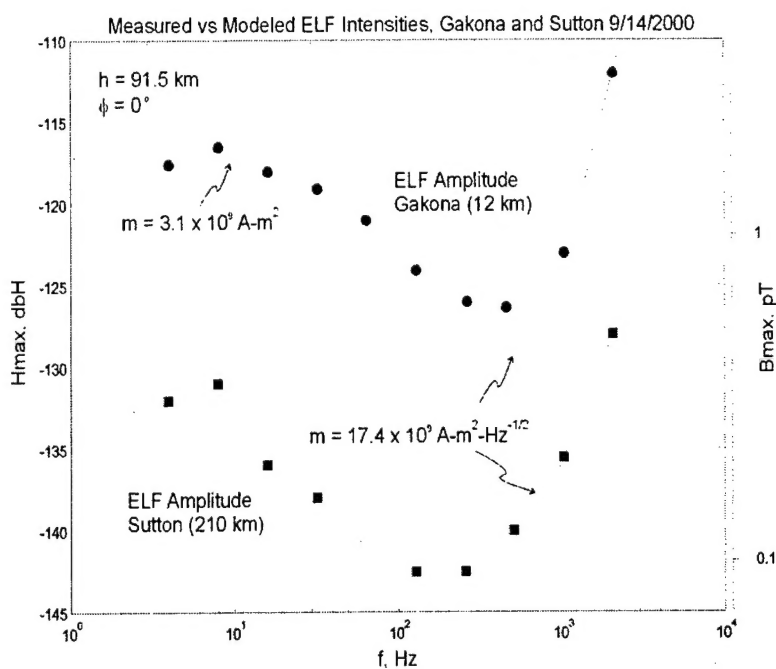
The data from four nights at the four distances has been spectrally analyzed and it is clear that excellent data were obtained at all distances out to 200 km from HAARP. The frequency range with good data includes 4, 8, 16, 32, 64, 128, 256, 512, 1000, 2000 and 4000 Hz. At the remote sites the 4 Hz signal generally had the best signal-to-noise ratio, with 64 to 512 Hz. having the poorest.



All the field data were copied from the digital tapes to the DVD format, with a spare set for backup. Sample data from each night, at each site were spectrally analyzed to determine the quality of the data obtained from each of the sixteen sites. The frequency range with good data includes 4, 8, 16, 32, 64, 128, 256, 512, 1000, 2000 and 4000 Hz at all distances out to 200 km. The total sampled data for the campaign comprised approximately 40 GB.

### Data Analysis

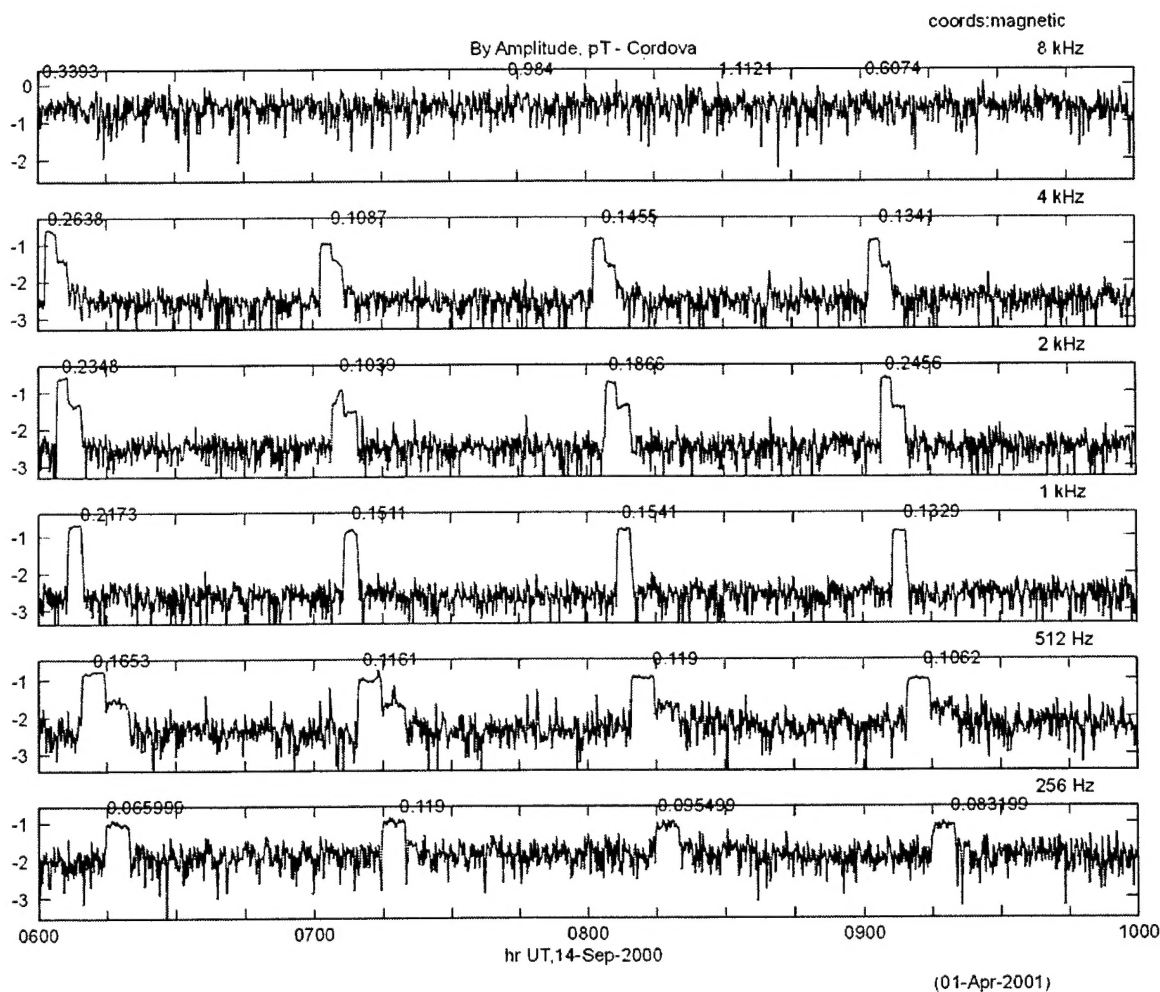
Several kinds of data analyses were performed on the observations. For the antenna pattern study the amplitudes of the B components were normalized with respect to the corresponding Gakona signals. For example, Figure 5. shows the amplitude vs. frequency for Gakona and a 200 km site, Sutton. Corresponding data for all sites were used to compare with theoretical antenna patterns for various frequencies. This study is being prepared for publication.



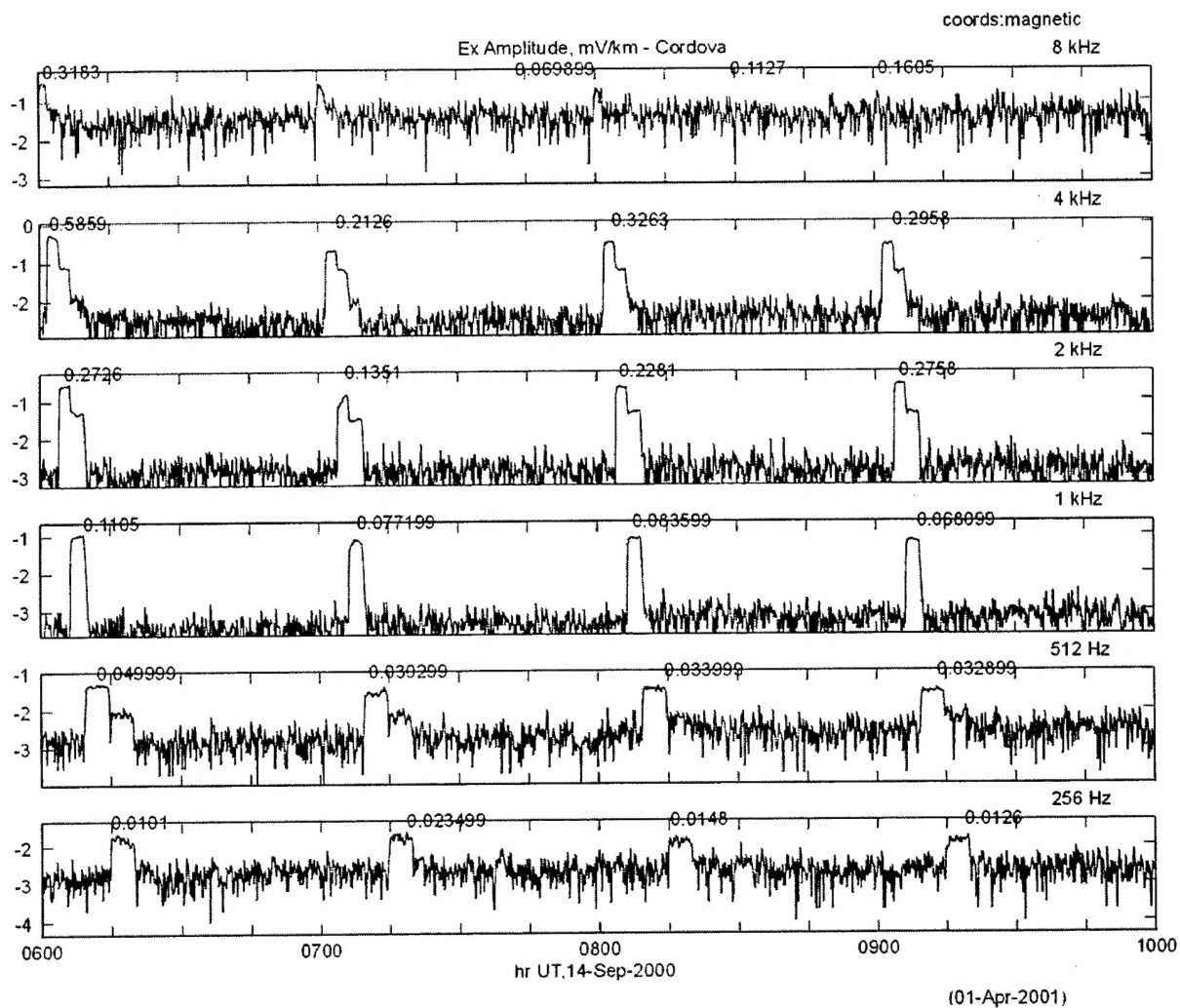
**Figure 5.** Comparison of the amplitude vs. frequency of the recorded HAARP signal strength vs. frequency at the reference Gakona site and at the 200 km distant Sutton site. The curves are the theoretical predictions.

The data from the north and east sites comprised signals sampled at 4096/sec due to operator error, while the west and south sites were sampled at 8196/sec. Amplitude calibrations for each of the electric and magnetic channels were applied to the data to produce absolute signal levels. From these sampled data the amplitude and phase were computed for each of the individual frequencies 4, 8, 16, 32, 64, 126, 256, 1000, 2000 Hz and 4000 Hz for the 8196/sec records.

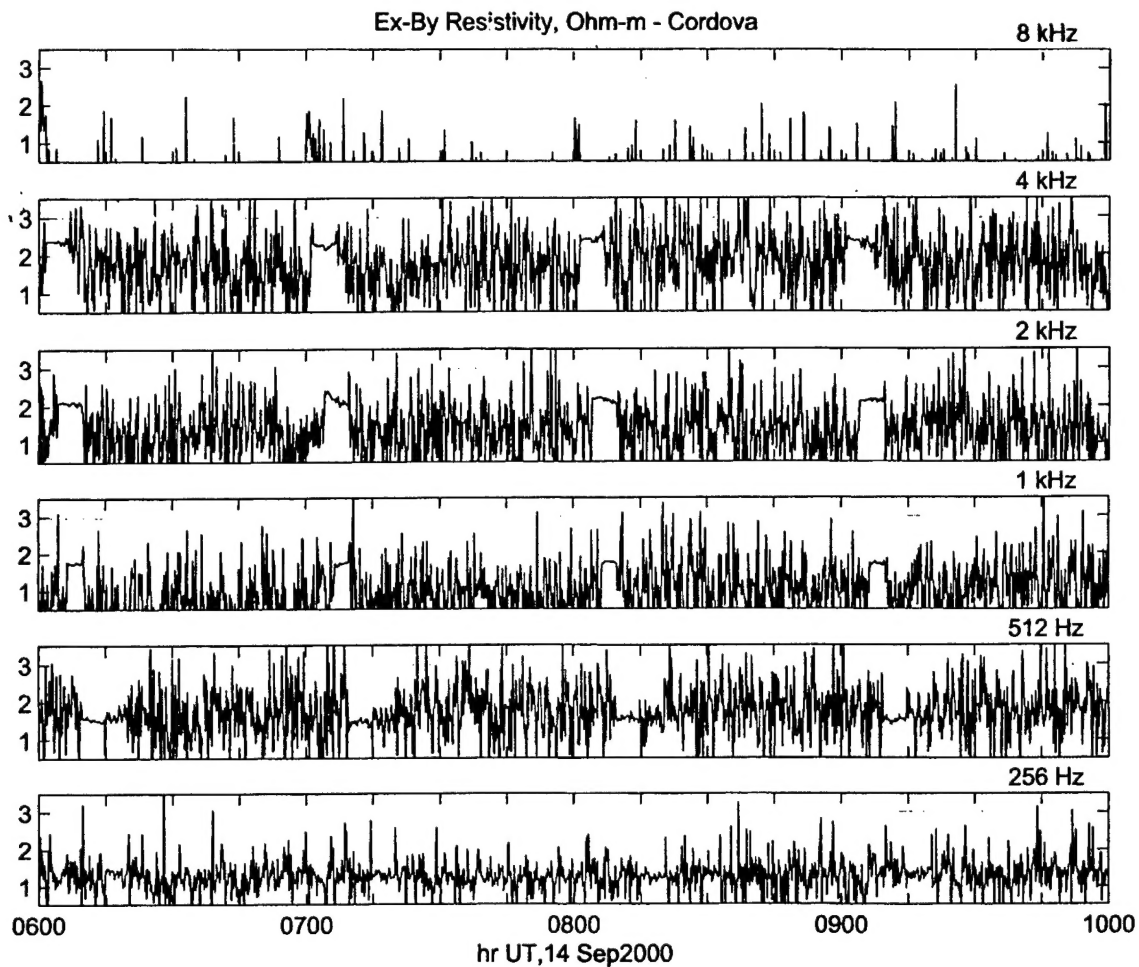
Figure 6 shows sample results 256-4000 Hz for the **By** channel obtained from Cordova on 14 September 2000. Figure 7 shows the corresponding results for the **Ex** channel. The Cagniard resistivity could also be calculated and plotted by the computer as shown in Figure 7. Note that the resistivity is not constant with time, indicating changes in the antenna pattern with time. This may be due to changes in direction of the electrojet affected by the HAARP signal.



**Figure 6.** Amplitude in pT (logarithmic) of **Bx** component vs. time, at the 200 km distant site, Cordova, for the frequencies 256 Hz to 4 KHz. There is no signal at 8 kHz due to the sampling rate of only 8192.



**Figure 7.** Amplitude in mV/km of Ex corresponding to the same frequencies of Figure 6. The amplitudes are logarithmic.



**Figure 8.** Computer generated Cagniard resistivity using the **Ex** and **By** amplitudes shown in Figures 6 and 7, in  $\Omega\text{-m.}$ , for Cordova, log amplitude scale. Note that the value of the resistivity sometimes varies with time. This must be due to changes in the ionosphere, possibly the direction or location of the electrojet.

## Summary and Conclusions

Several years of preliminary experiments using HIPAS and HAARP were required to refine equipment, field procedures, recording, and analysis programs. Permission was obtained to operate on land at 16 field stations surrounding HAARP at distances of 50, 100, 150 and 200 km. We determined the virtual antenna pattern of HAARP during a two-week field program in fall, 2000. The recorded signal data using both **E** and **B** was used to compute the apparent Cagniard resistivity at frequencies from 4 to 4000 Hz. The very best signal to noise was found at 4 Hz. The work has shown that modulated HAARP signals can be used to determine the ground resistivity vs. depth to a distance of at least 200 km from HAARP. The signal to noise is a function of frequency, with best signal to noise generally from 4 to 32 Hz and from 1000 to 4000 Hz., with minimum from 64 to 512 Hz. The apparent resistivity at a particular frequency is not constant, presumably due to changes in the ionosphere or the direction of the electrojet current, as the ground resistivity itself is not changing. This was illustrated in Figure 8 from data at the 200 km distant station near Cordova. Cell phone communication between the four field crews and with HAARP was spotty, which did not allow real time changes to the schedule. Normally we operated on the HAARP program, which involved a schedule of frequencies transmitted and recording of all the received data. The other program called CSAMT would involve the same frequencies, but the apparent resistivity, phase and cross correlation coefficient would be calculated in near real time. We did not schedule the CSAMT program until we had recorded a good night of the HAARP mode. Every night that we tried the CSAMT program it was quiet, with very low signal levels. Thus all the resistivity data were derived after the fact from the HAARP mode recordings.

The unpredictability of HAARP derived signal strength on any particular night is a drawback to commercial use of HAARP as a CSAMT source for exploration. In the program we conducted, 4 Hz was the lowest frequency transmitted. This restricted the skin depth, or depth of penetration to a few km. Any application to oil and gas exploration would require HAARP be modulated at lower frequencies, with skin depths to tens of km. We recommend a future field test using frequencies below 1 Hz to demonstrate the use of HAARP for deeper structural exploration.

## Appendix A

### The CSAMT and Portable Antenna Pattern Measurement Equipment

Zonge Engineering and Research Organization GDP-32 II multi-function receiver.

- |                     |  |
|---------------------|--|
| • Description       | Broadband, Multi-channel digital electromagnetic receiver  |
| • Frequency Range   | DC to 8 kHz  |
| • Channels          | 5  |
| • Software language | C++ and assembly, Windows  |
| • Time base         | Oven controlled crystal oscillator with $5 \times 10^{-10}$ per 24 hours aging rate plus GPS-disciplining option |
| • Power:            | 12 rechargeable batteries.   |

- Input impedance       $10\text{M}\Omega$  at DC
- Dynamic Range        190 dB

#### Magnetometer coils

- Zonge Engineering Type 3: linear 4 HZ to 8 kHz at 100 mV/nT

#### References

Bostick, F.X., Jr. A simple and almost exact method of MT analysis. In Ward, S.H., ed., Workshop on Electrical Methods in Geothermal Exploration, Snowbird, Utah,: University of Utah, Salt Lake City, Utah 84112, pps. 175-183 1976.